Rb-Sr and Sm-Nd ISOTOPIC ANALYSES OF QUE 94201: CONSTRAINTS ON MARTIAN DIFFERENTIATION PROCESSES.
L. E. Borg[1], L. E. Nyquist[1], L. A. Taylor[2], H. Wiesmann[3], and C. -Y. Shih[3], [1]Code SN41, NASA Johnson Space Center, Houston, TX 77058, [2]Planetary Geosciences Institute, Dept. of Geological Sciences, University of Tennessee, Knoxville, TN 37996, [3]Code C23, Lockheed Martin, 2400 NASA Road 1, Houston, TX 77258.

Introduction and Background: The Martian meteorite QUE 94201 is a recently identified basaltic shergottite. Although QUE 94201 has abundances of major elements that are roughly similar to the other shergottites, it demonstrates the most extreme geochemical fractionations of any Martian meteorite studied thus far [1]. The abundances of high field strength elements, middle rare earth elements (REE), and heavy-REE are significantly higher than in the other shergottites, whereas abundances of the most incompatible elements (e.g., Rb, K, Ta, and light-REE) are as low or lower than in the most depleted shergottites. These observations have led to the suggestions that 1) QUE 94201 was derived from a source that was strongly depleted through melting events, and 2) the melt was not significantly modified by the addition of the light-REE-enriched crustal component that is present in the other shergottites [2, 3]. Thus, isotopic analysis of QUE 94201 provides constraints on the mineralogy and composition of shergottite mantle sources, the extent and timing of melting events on Mars, and petrogenetic relationships among the individual meteorites.

Analytical Procedure: A 330 mg split of QUE 94201, 31 was crushed in a boron carbide mortal and pestle. Two splits were set aside for whole-rock isotopic analysis and the remainder was sieved at 74-150 μm and 44-74 μm. The fine size fraction (44-74 μm) was leached in warm 1N HCl yielding a whole rock leachate and a residue from which mineral fractions were separated using heavy liquids and hand-picking. Minerals were separated from the coarse size fraction (74-150 μm) using a Franz magnetic separator and hand-picking. These mineral fractions were leached in warm 1N HCl prior to digestion. Rb-Sr and Sm-Nd were separated using cation specific resins and micro columns. Sm and Nd were separated using AG50X8 (NH_4) form and α-hydroxyisobutyric acid. All samples were run statically on a multi-collector Finnigan MAT 261 mass spectrometer. Nd was run as an oxide and as a metal, depending on the size of the load.

Isochrons: Isotopic analyses of mineral, leachate, and whole rock fractions from QUE 94201 yield Rb-Sr and Sm-Nd crystallization ages of 327±12 Ma and 327±19 Ma respectively (Figs. 1, 2). These ages are older than the preliminary Rb-Sr age reported in [4] as a result of a mathematical error. The Rb-Sr and Sm-Nd ages are concordant, although the isochrons are defined by different fractions within the meteorite. Comparison of isotope dilution Sm and Nd data for the various QUE 94201 fractions with in situ ion microprobe data of minerals [5] demonstrates the presence of a leachable non-igneous crustal component in the meteorite. The addition of the crustal component can affect the isochrons by selectively altering the isotopic

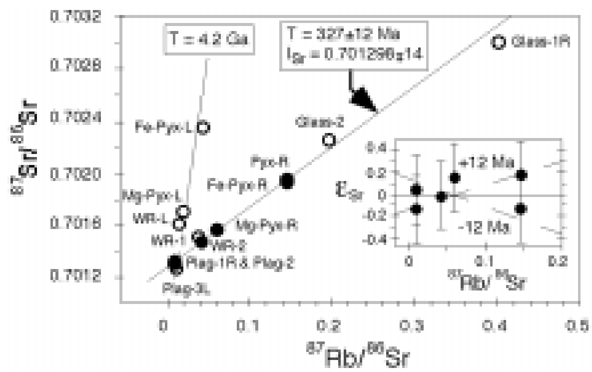

Figure 1. Rb-Sr isochron plot of mineral, leachate, and whole rock fractions from QUE 94201. A crystallization age of 327±12 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.701298±14 is defined by maskelynite (Plag-1R, Plag-2), pyroxene (Mg-Pyx-R, Fe-Pyx-R, Pyx-R), and whole rock (WR-2) fractions (solid circles) using $\lambda(^{87}Rb)$ = 0.01402 $(Ga)^{-1}$. Open circles are fractions not used to define isochron. (R and L denote residues and leachates).

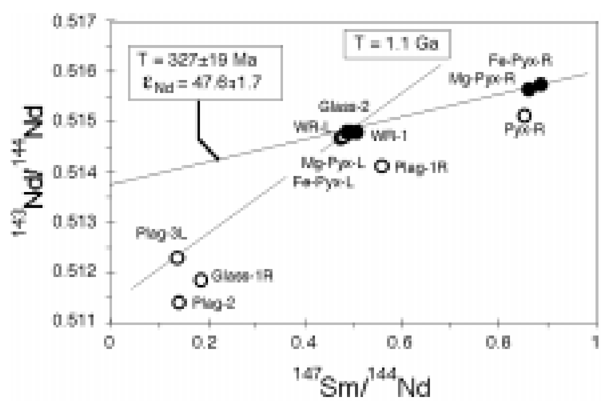

Figure 2. Sm-Nd isochron plot of mineral, leachate, and whole rock fractions from QUE 94201. A crystallization age of 327±19 Ma and initial an ε_{Nd} of 47.6±1.7 is defined by pyroxene (Mg-Pyx-R, Fe-Pyx-R, Pyx-R), whole rock (WR-2), and whole rock leachate (WR-L) fractions (solid circles). Open circles fractions not used to define isochron. (R and L denote residues and leachates).

systematics of some of the analyzed fractions. The presence of the crustal component 1) affects the Sm-Nd, but not the Rb-Sr systematics of the maskelynite, 2) affects the Rb-Sr, but not the Sm-Nd of the whole rock and whole rock leachate, and 3) does not appear to affect either the Rb-Sr nor the Sm-Nd systematics of the pyroxenes. The susceptibility of particular mineral fractions to isotopic perturbation is plausibly determined by a combination of their resistance to chemical alteration and their igneous concentrations of Rb-Sr and Sm-Nd.

Initial $^{87}Sr/^{86}Sr$, ε_{Nd}^{143} and whole rock ε_{Nd}^{142}, and partial melting models: Initial ^{87}Sr/^{86}Sr and ε_{Nd}^{143} of 0.701298 and 47.6 respectively, and ε_{Nd}^{142} of 0.92 indicate that QUE 94201: 1) was derived from a source that was strongly depleted in ^{87}Rb/^{86}Sr and enriched in ^{147}Sm/^{144}Nd early in its history, and 2) could have assimilated only a small amount of incompatible-element enriched crustal component. Partial melting models demonstrate that the Sm-Nd isotopic composition of QUE 94201 can be produced by melting a single source at 4.525 Ga and 327 Ma that has 2 times chrondritic REE abundances (Fig. 3). The source must be melted numerous times and contain garnet in order to produce a melt with the high ^{147}Sm/^{144}Nd of QUE 94201 (i.e. 0.503). The timing of the initial melting event is not uniquely fixed by the ε_{Nd}^{142} of QUE 94201 because it is also dependent on the Sm/Nd of the source. However, to produce a melt with ε_{Nd}^{142} of 0.92 from a source that was depleted later than 4.525 Ga requires the source to have ^{147}Sm/^{144}Nd that is higher than the modeled value of 0.281 (Fig. 3), and results in an initial ε_{Nd}^{143} value that is higher than the observed value of 47.6. Thus, the models imply that Martian mantle differentiation was early and extreme.

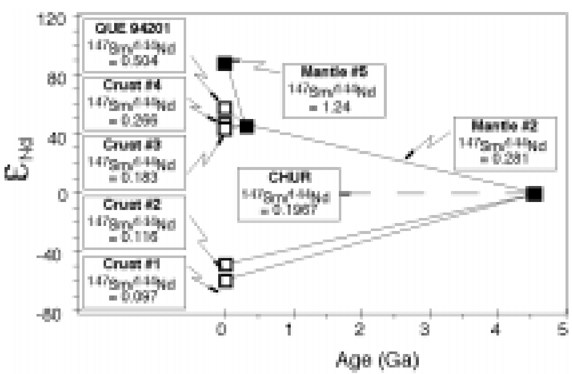

Figure 3. T-I diagram illustrating the results of partial melting models. Multi-stage melting models reproduce the Nd, Sm concentrations, ^{147}Sm/^{144}Nd, ^{143}Nd/^{144}Nd, and ^{142}Nd/^{144}Nd measured in QUE 94201 starting with 2xCI abundance of Sm and Nd. Initial melting occurs 33 Ma after solar condensation producing crust #1. A second melting event at the same time produces crust #2 and mantle #2. We assume that later melting events are contemporaneous with QUE 94201 melt production and result in crusts #3, #4, and QUE 94201.

Rb-Sr-based partial melting models are unable to reproduce the Sr isotopic composition of QUE 94201 using the same model parameters employed in the Sm-Nd-based models, underscoring a decoupling of Rb-Sr and Sm-Nd isotopic systems. The decoupling of the Rb-Sr and Sm-Nd systems results from numerous melting events which effectively fractionate Rb from Sr (into crustal and mantle reservoirs), but not Sm from Nd. The fact that all Martian meteorites

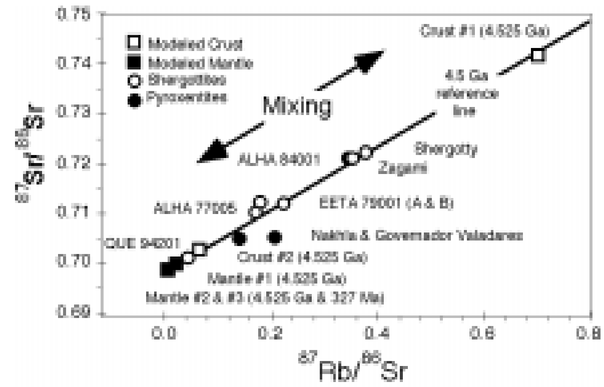

Figure 4. Rb-Sr plot of shergottite and nakhlite whole rocks, and modeled crustal and mantle sources calculated at 180 Ma. Ages behind the modeled mantle and crustal sources represent the time they were produced. Shergottite and nakhlite data from [6, 7, 8, 9, 10, 11]. The shergottites and nakhlites fall on a line with a slope corresponding to an age of 4.5 Ga between modeled mantle and crustal sources. Crust #1 has high ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr and lies on the 4.5 Ga reference line because it was extracted from the mantle at 4.525 Ga. The modeled mantle has very low ^{87}Sr/^{86}Sr as a result of efficient extraction of Rb by early differentiation processes. The shergottites and nakhlites have measured ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr values that are higher than the modeled mantle compositions, suggesting that they are mixtures of old crustal and young mantle sources.

analyzed so far define a Rb-Sr whole rock isochron age of 4.5 Ga (Fig 4) suggests that virtually all Rb was partitioned into the crust at this time. This is supported by the fact that the isotopic compositions of mantle and crustal reservoirs calculated from the partial melting models also lie on the 4.5 Ga Rb-Sr isochron (Fig. 4). The Rb-depleted Martian mantle is, therefore, not expected to evolve past a ^{87}Sr/^{86}Sr value of 0.700. Martian meteorites with ^{87}Sr/^{86}Sr greater than ~0.700 are likely to be produced by mixing between crustal and mantle reservoirs. The observation that the QUE 94201 leachates define mixing lines with slopes that are subparallel to the 4.5 Ga Rb-Sr (and 1.3 Ga Sm-Nd) whole rock isochrons indicates that mixing between various (presumably crustal and mantle) Martian reservoirs can produce the Rb-Sr and Sm-Nd isotopic systematics of Martian meteorites.

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